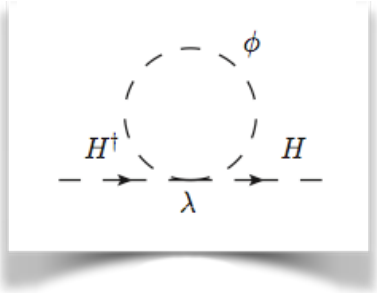
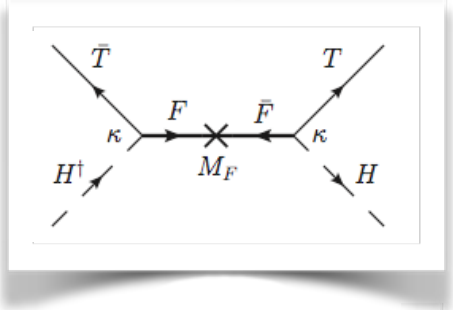
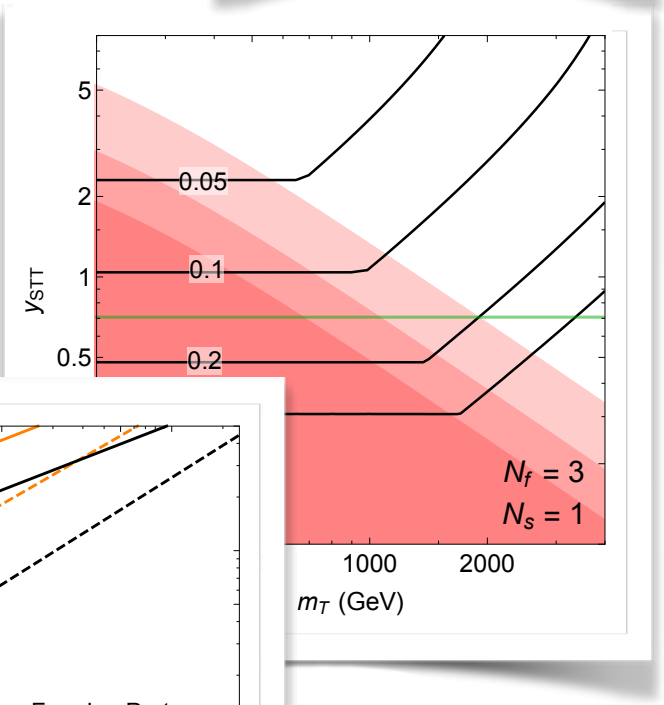
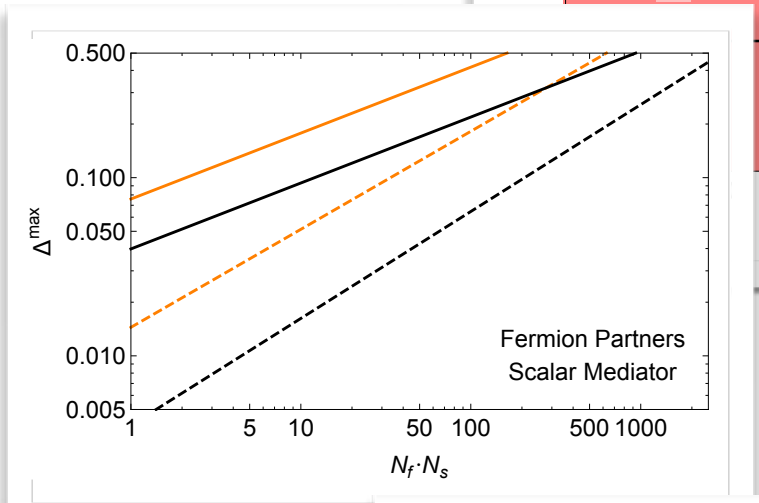
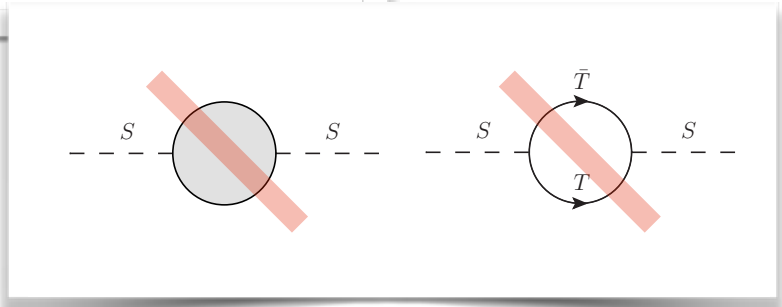
Towards A No-Lose Theorem For Naturalness











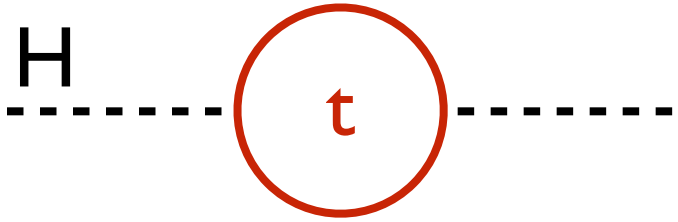
Parallel Talk
BNL Forum 2015
Brookhaven, NY

7. October 2015

David Curtin
University of Maryland

based on
DC, Saraswat 1509.04284
DC, Verhaaren 1506.06141

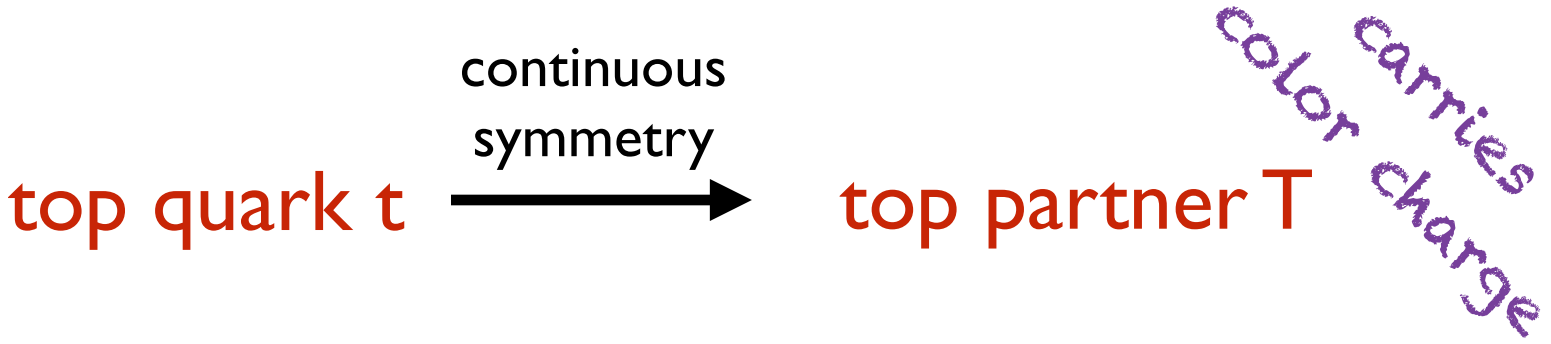
The Hierarchy Problem



… can be solved by top partners

The Hierarchy Problem

… can be solved by top partners

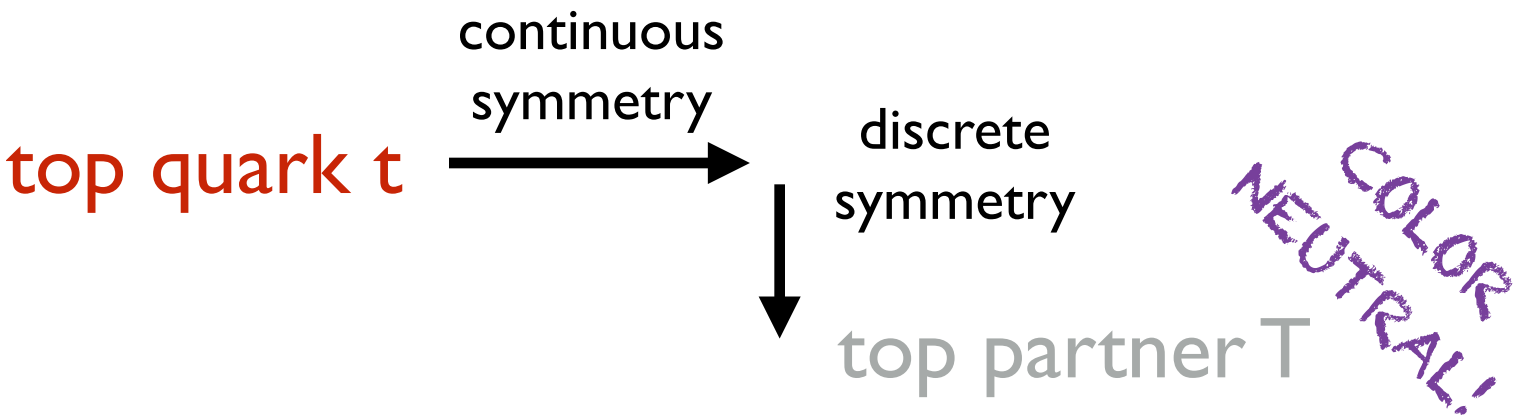


e.g.

***Supersymmetry**, modern **composite Higgs** models, etc…*

The Hierarchy Problem

A discrete symmetry can make the top partner **uncolored**.



e.g.

Folded SUSY *(EW-charged stops),* ***Twin Higgs*** *(SM singlet T-partners)*

hep-ph/0609152 Burdman, Chacko, Goh, Harnik

hep-ph/0506256 Chacko, Goh, Harnik

Neutral Naturalness

Why would we think about this?

1. The LHC is *great* at making colored particles, but so far no top partner discovery…

2. Want to examine naturalness as generally as possible: **test the mechanism, not the model!**

Neutral Naturalness generates radically different phenomenology from colored partners!

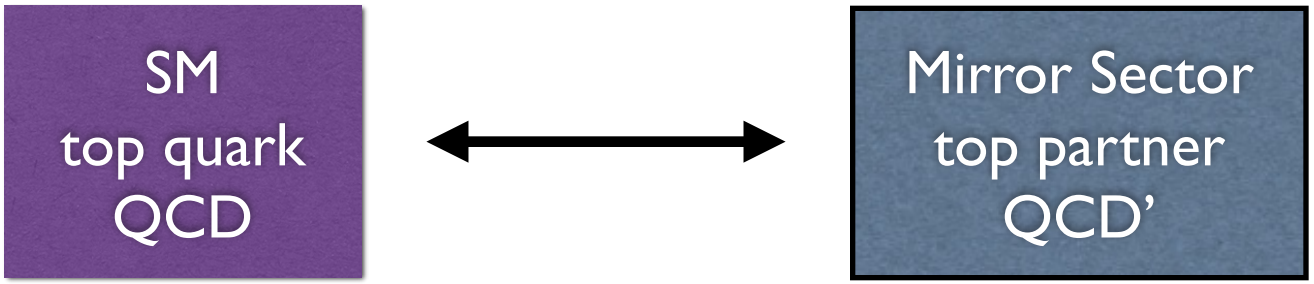
Neutral Naturalness

How to detect it?

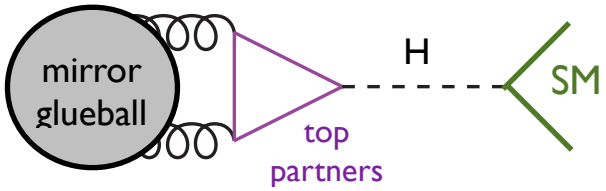
c.f. Strassler, Zurek '06 etc..

One possibility: Hidden Valley Phenomenology!

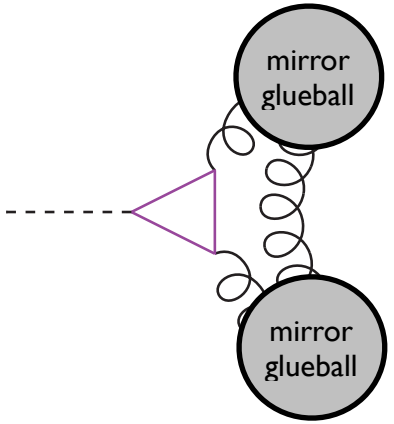
In these theories, the discrete symmetry usually copies SM QCD to a mirror sector in which the partners live.



Mirror gluons talk to the Higgs via top partner loops.



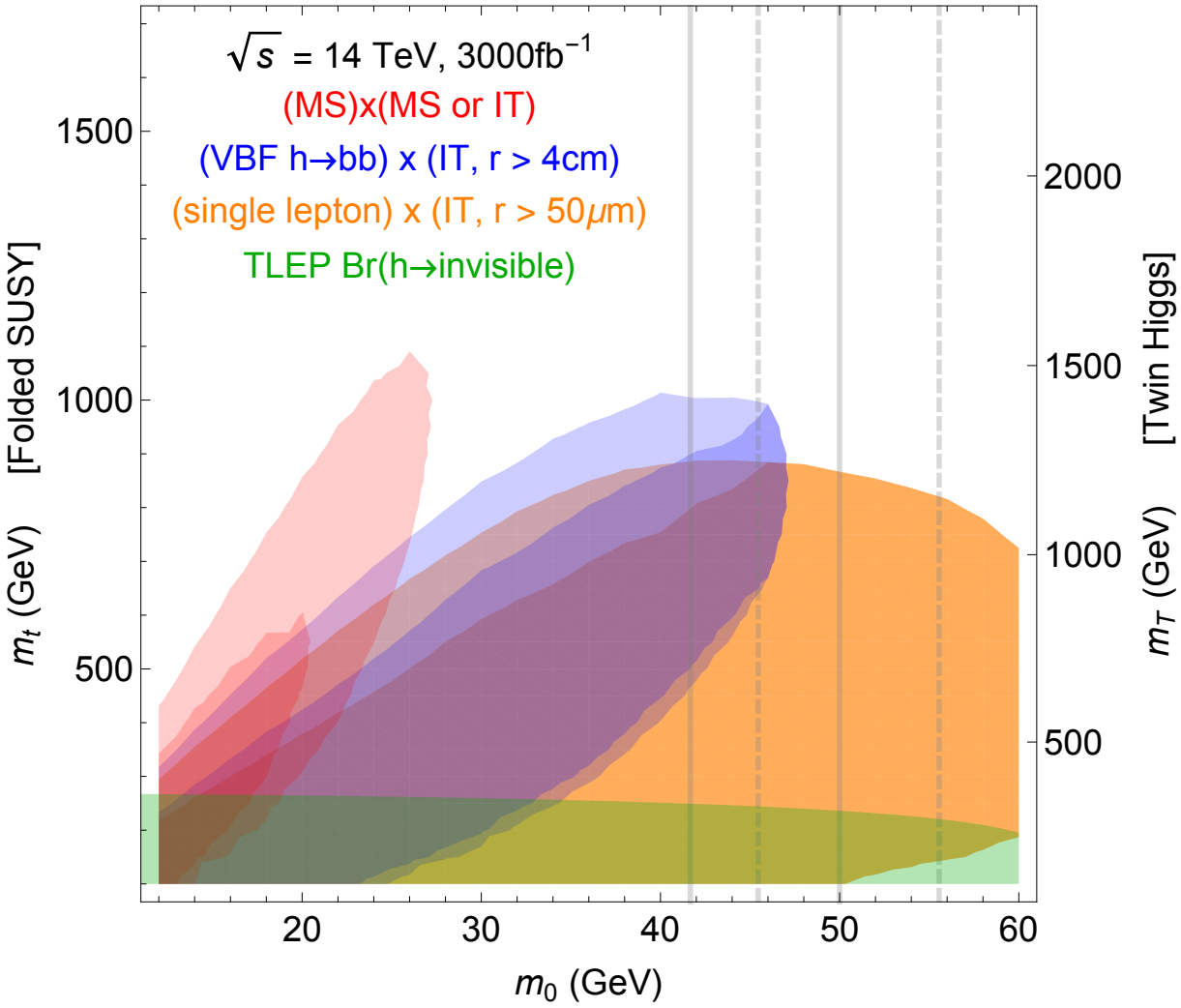
Allows for production and (displaced!) decay of mirror hadrons!



1501.05310 Craig, Katz, Strassler, Sundrum

Neutral Naturalness

Exotic Higgs decays to **long-lived** mirror glueballs give TeV-scale top partner reach at the LHC!



This signature is "**guaranteed**" for EW-charged top partners (FSUSY), and **possible** for neutral top partners (TH)

DC, Verhaaren 1506.06141

Neutral Naturalness

Mirror-glueball signatures are great, but not guaranteed in all models of Neutral Naturalness.

What are the *unavoidable* signatures, at the LHC and at future lepton an 100 TeV colliders?

A No-Lose Theorem for Top Partner Theories

Top Partners with SM Charge

Start with TeV-scale top partners that carry SM charge.

If QCD: produce plenty, discover at LHC or 100 TeV.

If partners carry any EW charge, regardless of decay mode etc, will be detectable up to ~ 2+ TeV @ 100 TeV due to RG effects in DY spectrum measurements!

Alves, Galloway, Rudermann, Walsh 1410.6810

TeV-scale SM-charged partners ARE DISCOVERABLE regardless of model details!

Neutral Top Partners

We really only have one class of models for neutral top partners: **Twin Higgs**, which predicts Higgs coupling deviations ~ tuning at lepton colliders.

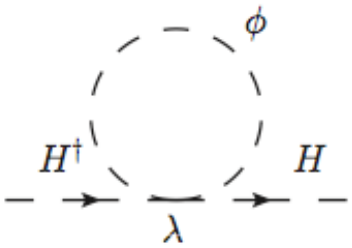
Is this general? Would like to understand signatures of neutral top partners **model-independently!**

→ **Bottom-Up EFT/Simplified Model Approach!**

DC, Saraswat 1509.04284

Four possible Neutral Top Partner structures

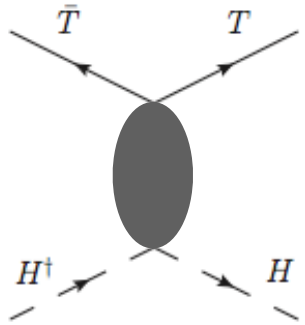
Scalar Partners



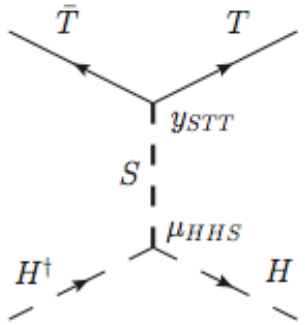
(Vector partners "same" as scalars)

Fermion Partners

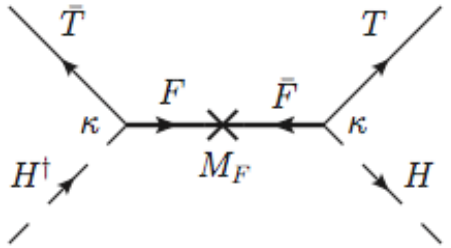
For fermion partners, have to distinguish how HHTT operator is generated.



Strong Coupling



Scalar Mediator



Fermion Mediator

Four possible Neutral Top Partner structures

Scalar Partners

Fermion Partners

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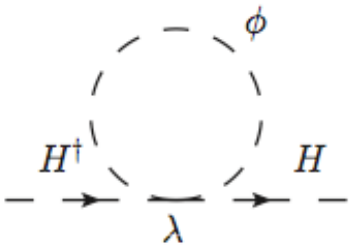

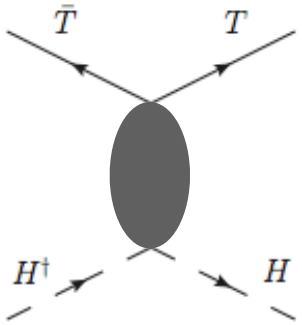

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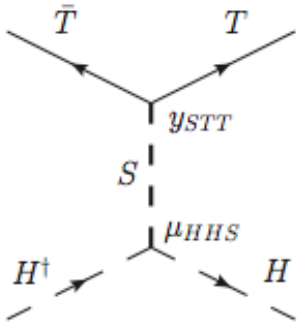
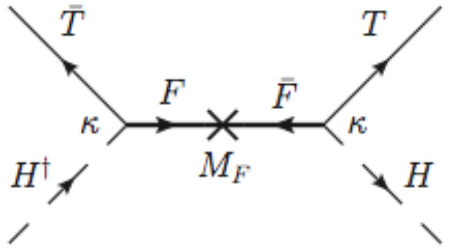


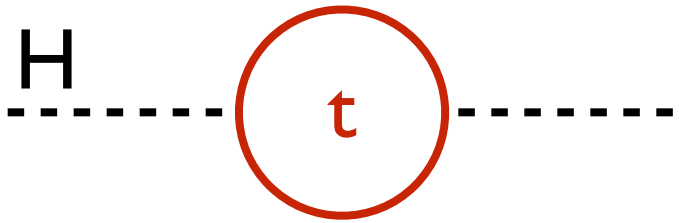
Scalar Mediator



Fermion Mediator

Only impose ***one*** condition on couplings:

cancellation of quadratic divergence from top loop

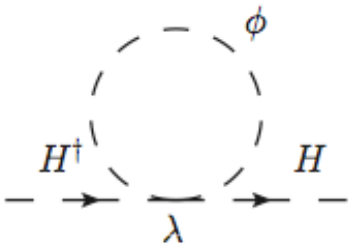


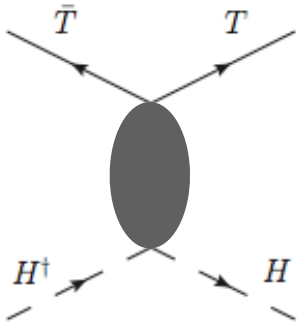
Four possible Neutral Top Partner structures

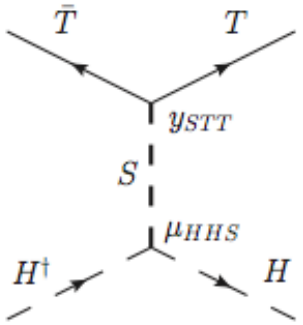
Scalar Partners

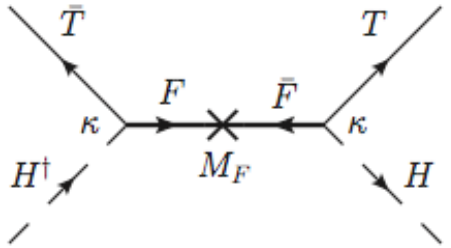
Fermion Partners

For fermion partners, have to distinguish how HHTT operator is generated.









Strong Coupling

Scalar Mediator

Fermion Mediator

?

Twin Higgs
with composite/ holographic UV completion

Twin Higgs
with perturbative UV completion

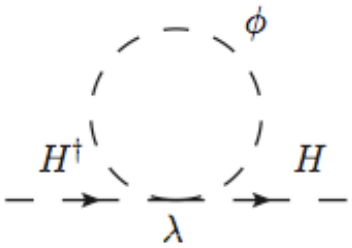
?

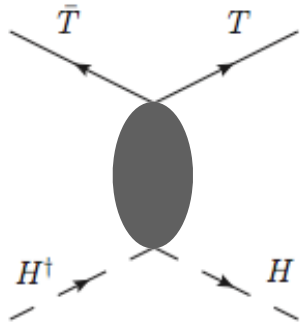
Four possible Neutral Top Partner structures

Scalar Partners

Fermion Partners

For fermion partners, have to distinguish how HHTT operator is generated.





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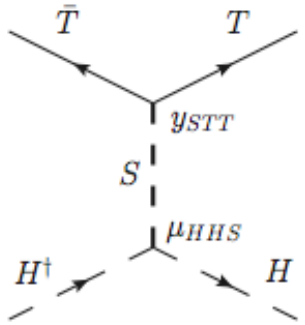
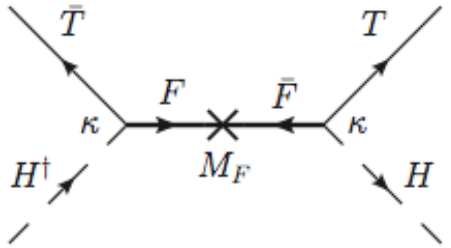


Scalar Mediator



Fermion Mediator

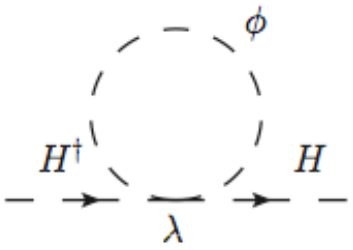
For each scenario, analyze:

Irreducible low-E signatures:

- Zh cross section (lepton collider)
- electroweak precision observables (lepton)
- higgs cubic coupling (100 TeV)
- top partner direct production (100 TeV)

Four possible Neutral Top Partner structures

Scalar Partners



Fermion Partners

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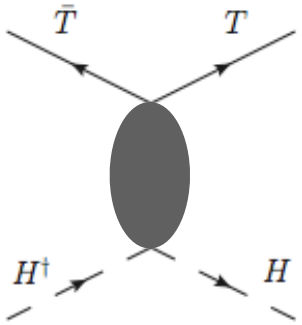

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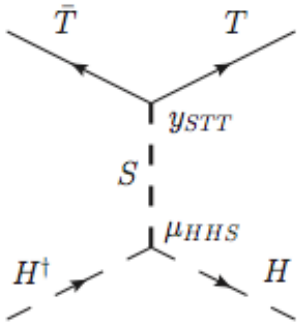
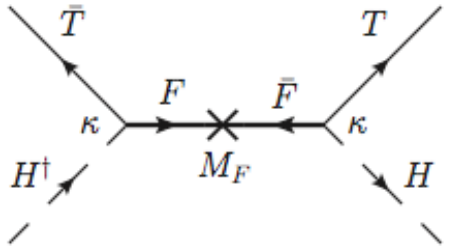


Scalar Mediator



Fermion Mediator

For each scenario, analyze:

Irreducible low-E signatures:

- Zh cross section (lepton collider)
- electroweak precision observables (lepton)
- higgs cubic coupling (100 TeV)
- top partner direct production (100 TeV)

Irreducible tunings $\{\Delta_i\}$ suffered by scenario $\Rightarrow$ $\Delta_{tot} = f(\Delta_i)$

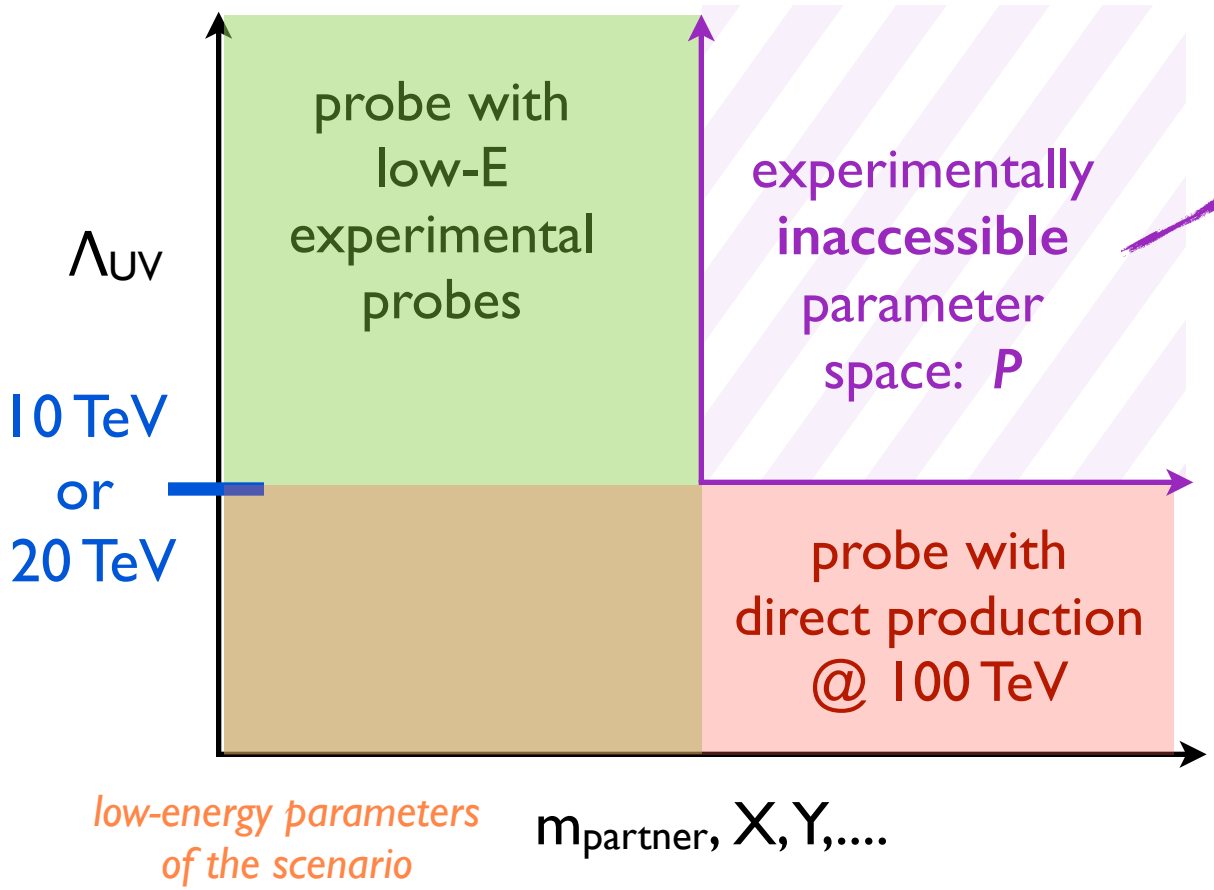
These will relate to UV completion scale Λ_{UV}.

Symmetry arguments suggest SM-charged BSM states at this scale

→ **production at 100 TeV collider!**

Strategy

For each scenario:



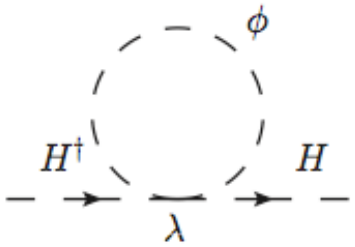
Find the LEAST TUNED the theory can be while escaping experimental detection:

$$\Delta_{tot}^{min} = \underset{\{P\}}{\text{Max}}\, f(\Delta_i)$$

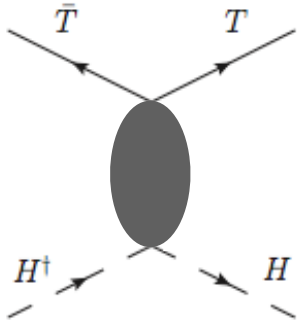
This will allow us to determine how natural an "undiscoverable" theory could be....

Neutral Naturalness Scenarios

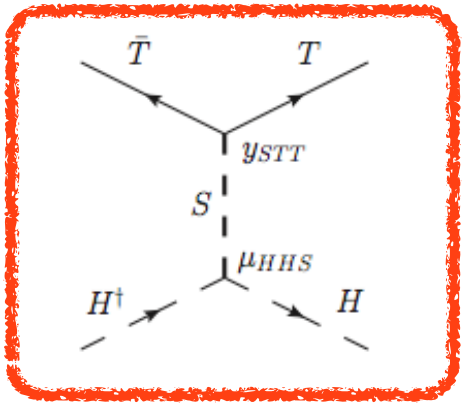
Scalar Partners



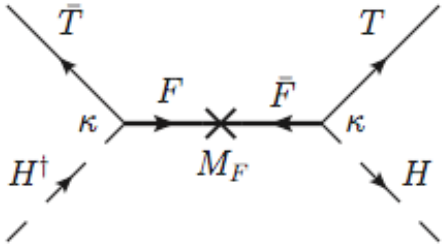
Fermion Partners
(strong coupling)



Fermion Partners
(scalar mediator)



Fermion Partners
(fermion mediator)



Trickiest/most interesting case
to analyze in complete generality...

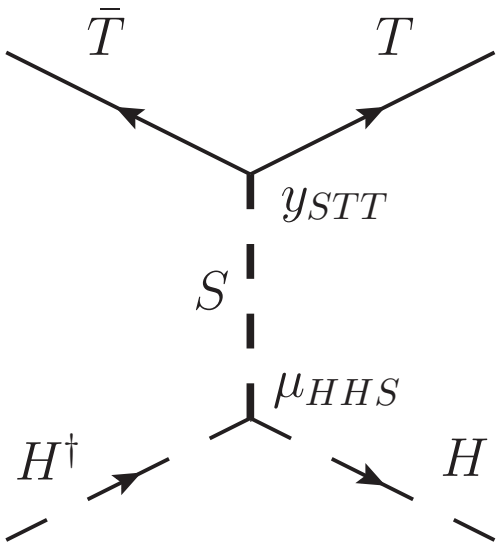
Fermion Partner - Scalar Mediator

This is the most complicated and important case.

Contains Twin Higgs & Orbifold generalizations,
but is much more general.

1410.6808, 1411.7393 Craig, Knapen, Longhi

$$\mathcal{L}_T \supset \sum_i T_i \bar{T}_i \left(M_{T_i} - \frac{|H|^2}{2M_i'} \right)$$



Integrate out mediator(s) to match to natural IR theory:

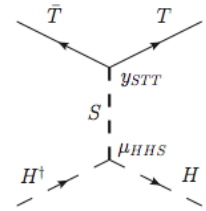
$$N_s \frac{\mu_{HHS} y_{STT}}{m_S^2} = \frac{1}{2M'} = \frac{3}{2N_f} \frac{y_t^2}{M_T}$$

Scalars are slippery....

SPOILER: higgs mixing & lots of tunings!

(familiar from TH, but derived completely model-independently)

Fermion Partner - Scalar Mediator



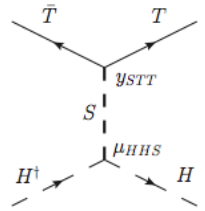
Before we can proceed, we have to know:
How heavy is the scalar mediator?

Naive expectation: new scalars can't be light, otherwise we have another hierarchy problem!
⇛ m_S should be significantly above weak scale!

Naive counterargument: we know of many ways to solve the hierarchy problem! Dress up mediator sector with partners etc...

Nope!

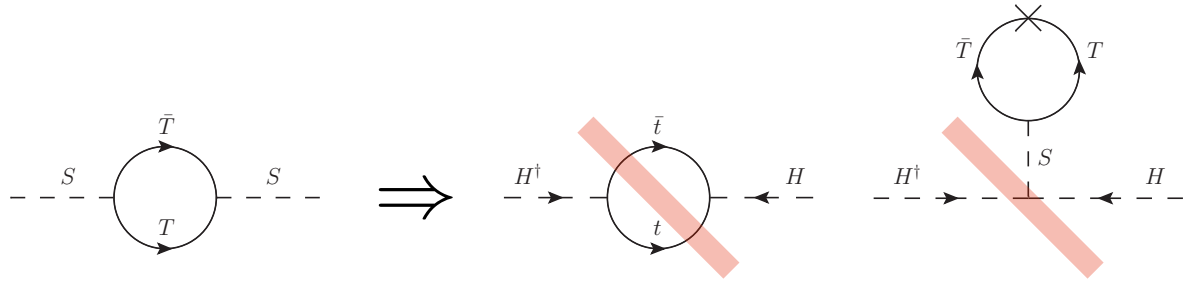
Fermion Partner - Scalar Mediator



Sacrificial Scalar Mechanism

S unprotected

H stabilized



S stabilized

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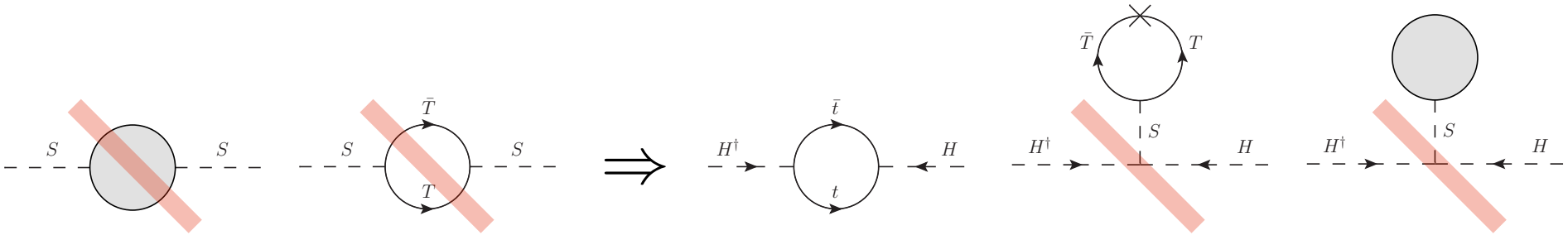
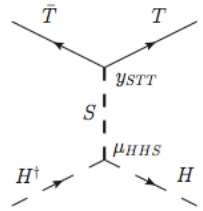


Consequences:

1. Mass of scalar is tied to UV completion scale!
2. $m_S >> m_h$ makes it easy to compute experimental signals.

Fermion Partner - Scalar Mediator



(for one mediator)

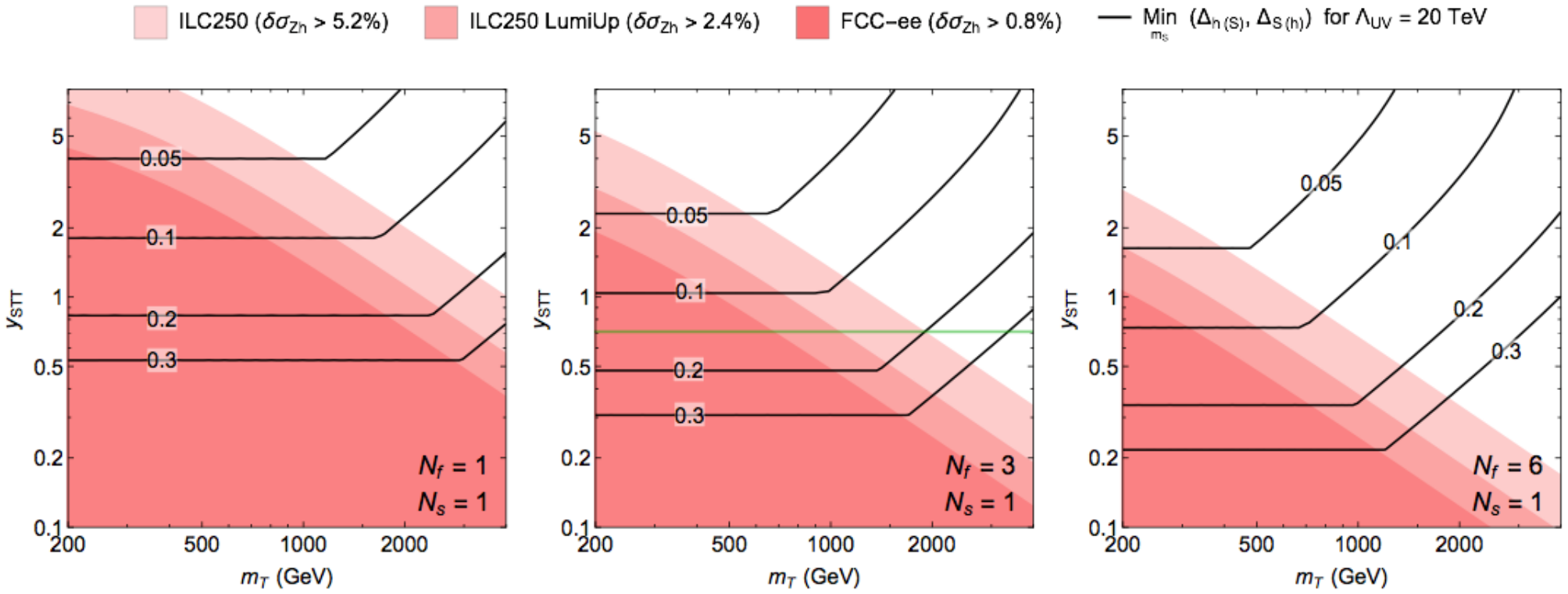
Higgs Mixing!

(familiar from TH)

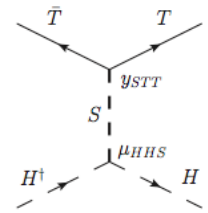
$$s_\theta \approx -\frac{\mu_{HHS}}{m_S^2} v$$

$$\delta\sigma_{Zh} \approx -\sum_i s_{\theta_i}^2 \approx -\frac{9}{4N_f^2 N_s} \frac{y_t^4}{y_{STT}^2} \frac{v^2}{M_T^2}$$

For given number of partners N_f, **mixing** (and hence $\delta\sigma_{Zh}$) is defined in **(m_T, y_{STT}) parameter space.**



Fermion Partner - Scalar Mediator



Tunings:

$\Delta_{h(S)}$ = log tuning of m_h from mediator loops.

(have to differentiate case where Higgs = PNGB from case without such symmetries....)

Gets worse with large m_S!

$\Delta_{S(T)}$ = tuning from quadratic sensitivity of m_S to T loops (required by Sacrificial Scalar Mechanism!)

Gets better with large m_S!

Can find conservative tuning estimate by maximizing over (unknown) mediator mass!

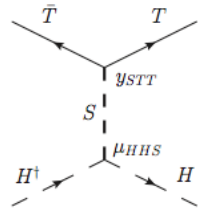
$$\Rightarrow \quad \Delta_{H,S} = \max_{m_S} f(\Delta_{h(S)}, \Delta_{S(T)})$$

is total 'additional' tuning from mediator sector!

$\Delta_{h(T)}$ = log tuning from incomplete t-T cancellation

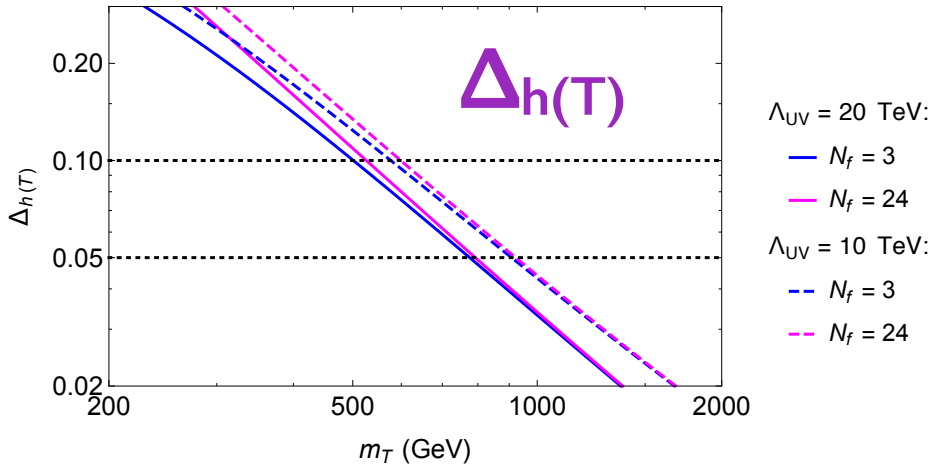
(wants m_T < 500ish GeV)

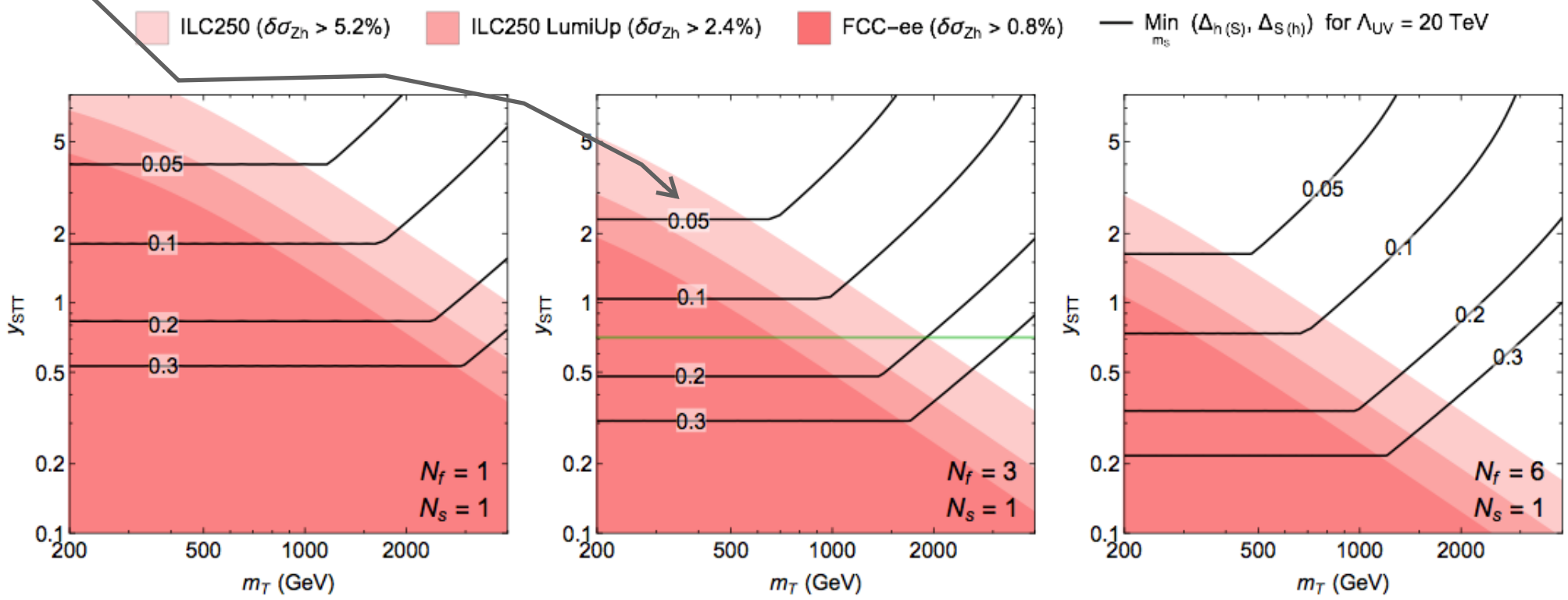
Fermion Partner - Scalar Mediator



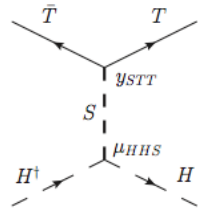
$$\Delta_{H,S} = \max_{m_S} f(\Delta_{h(S)}, \Delta_{S(T)})$$

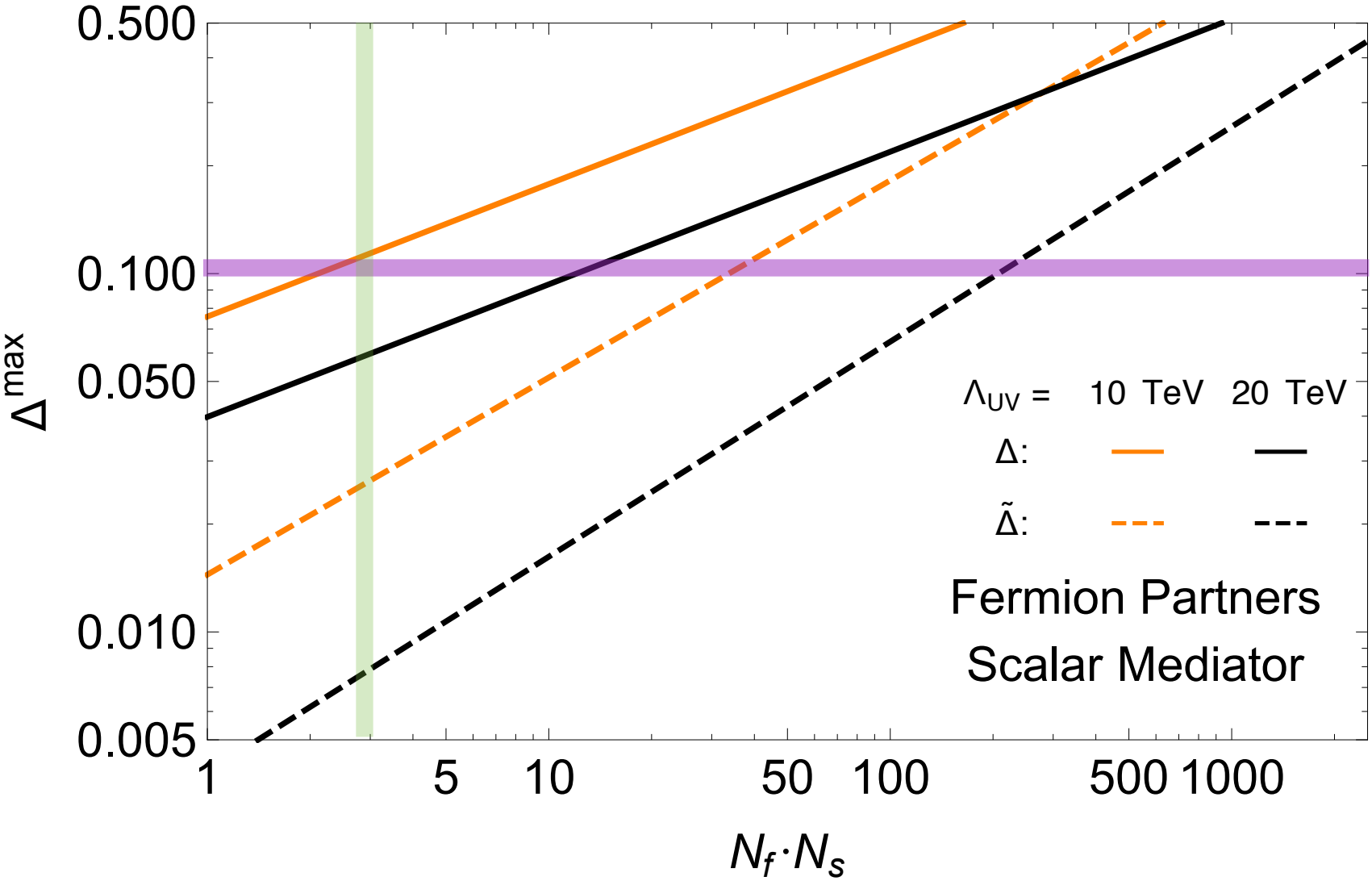
Can immediately see that
$N_f = 3$ has to be discoverable
or tuned worse than 10%!





Fermion Partner - Scalar Mediator





A natural theory needs to have VERY MANY fermion partners/scalar mediators to possibly escape detection.

.. similarly for the other scenarios

What's the upshot?

1. No-Lose Theorem:

Any theory of ~10% naturalness with O(SM) top partners will be discovered at lepton collider and/or 100 TeV

How to avoid this theorem?

Could have **top partner swarms, or neutral top partners without SM charges in UV completion.**

There might also be weird non-perturbative or stringy constructions that don't need top partners?

2. Implications for future colliders

*Both lepton collider **and** 100 TeV have to work **in tandem** for full coverage of **general naturalness***

Without lepton collider:

could miss theory with large-ish Higgs mixing but small hidden sector couplings → very high UV completion scale out of 100 TeV collider reach

Without 100 TeV:

several scenarios give small IR signatures, need to probe UV

3. Probing UV completion is vital!

Central assumption of SM-charged BSM states at Λ_{UV} allows us to make these very powerful conclusions.

This seems very reasonable, and is certainly the case in all currenty proposed UV completions.

Can we formally prove this always has to be the case, or construct counter-examples?

Summary

1. **No-Lose Theorem:**

   Any theory of ~10% naturalness with O(SM) top partners will be discovered at lepton collider and/or 100 TeV

2. **Implications for future colliders**

   *Both lepton collider **and** 100 TeV have to work **in tandem** for full coverage of **general naturalness***

3. **Probing UV completion is vital!**

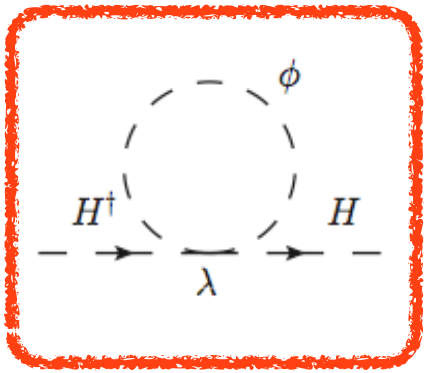
   *Can we **formally** prove that full that SM-charged BSM states appear at Λ_{UV} in full symmetry-based theories?*

Thank you!

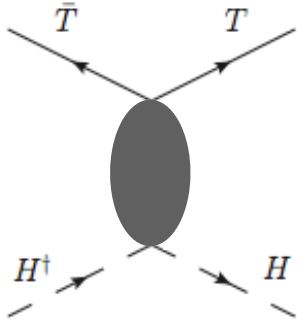
Backup Slides

Neutral Naturalness Scenarios

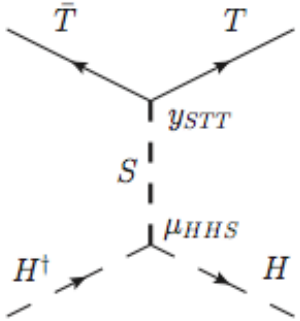
Scalar Partners



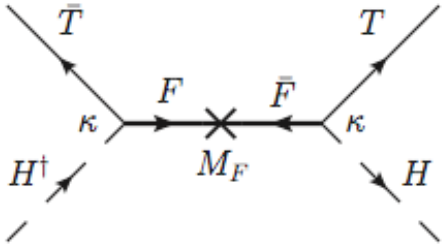
Fermion Partners
(strong coupling)



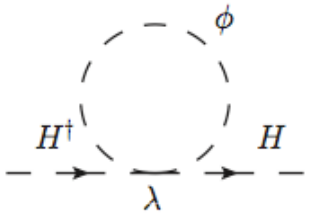
Fermion Partners
(scalar mediator)



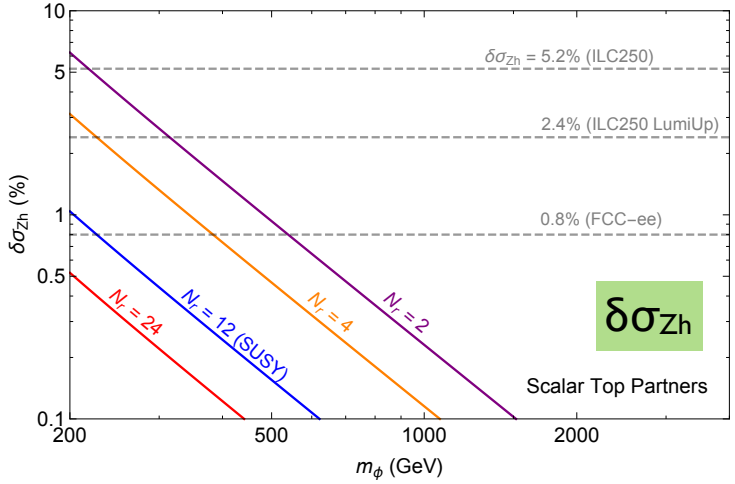
Fermion Partners
(fermion mediator)

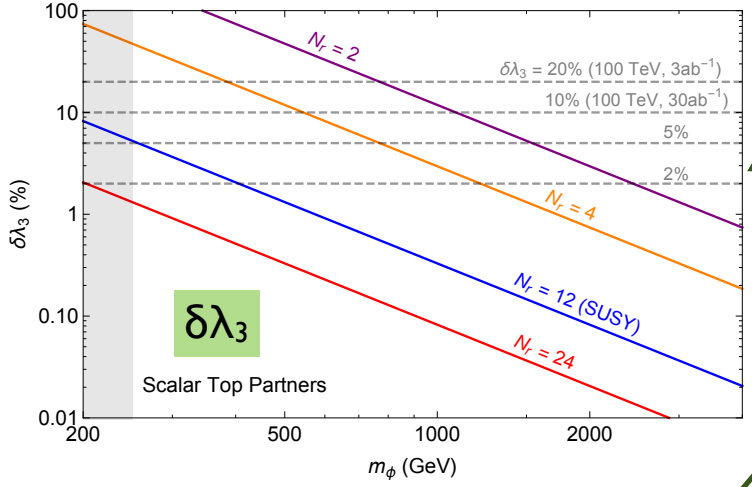


Scalar Partner



1305.5251 Craig, Englert, McCullough





Low-energy probes only have reach of few 100 GeV

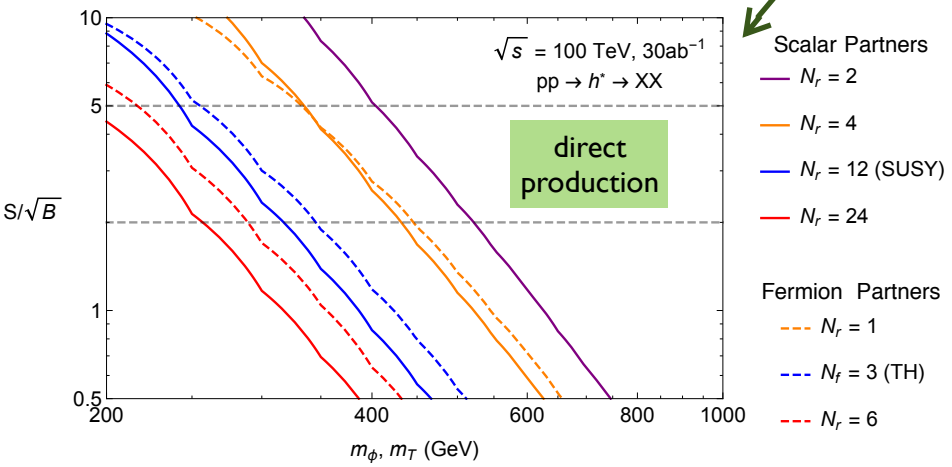
Two tunings in theory:

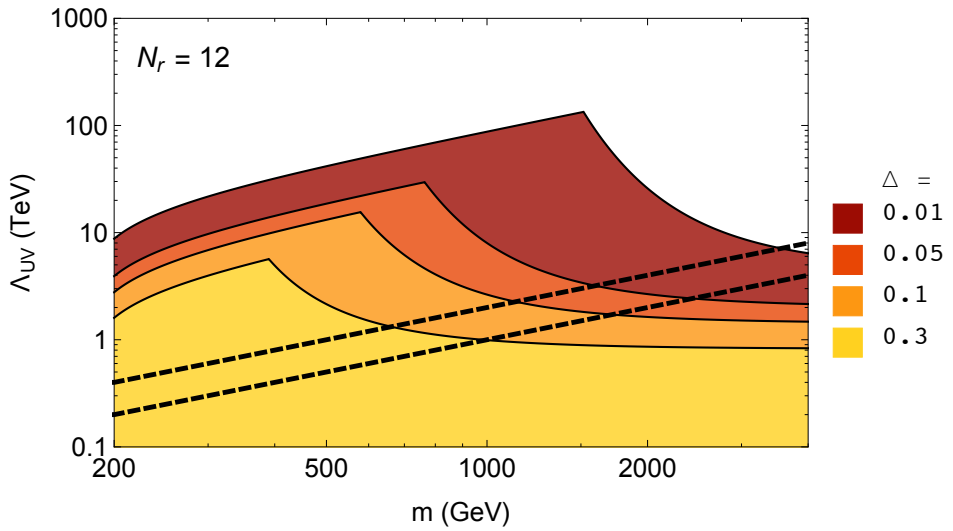
$\Delta_{h(\phi)}$ = log tuning from incomplete t-ϕ cancellation

$\Delta_{\phi(h)}$ from quadratically divergent mass contribution due to higgs loops

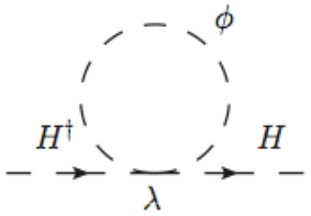
For given Δ_{tot}, find largest allowed Λ_{UV}:

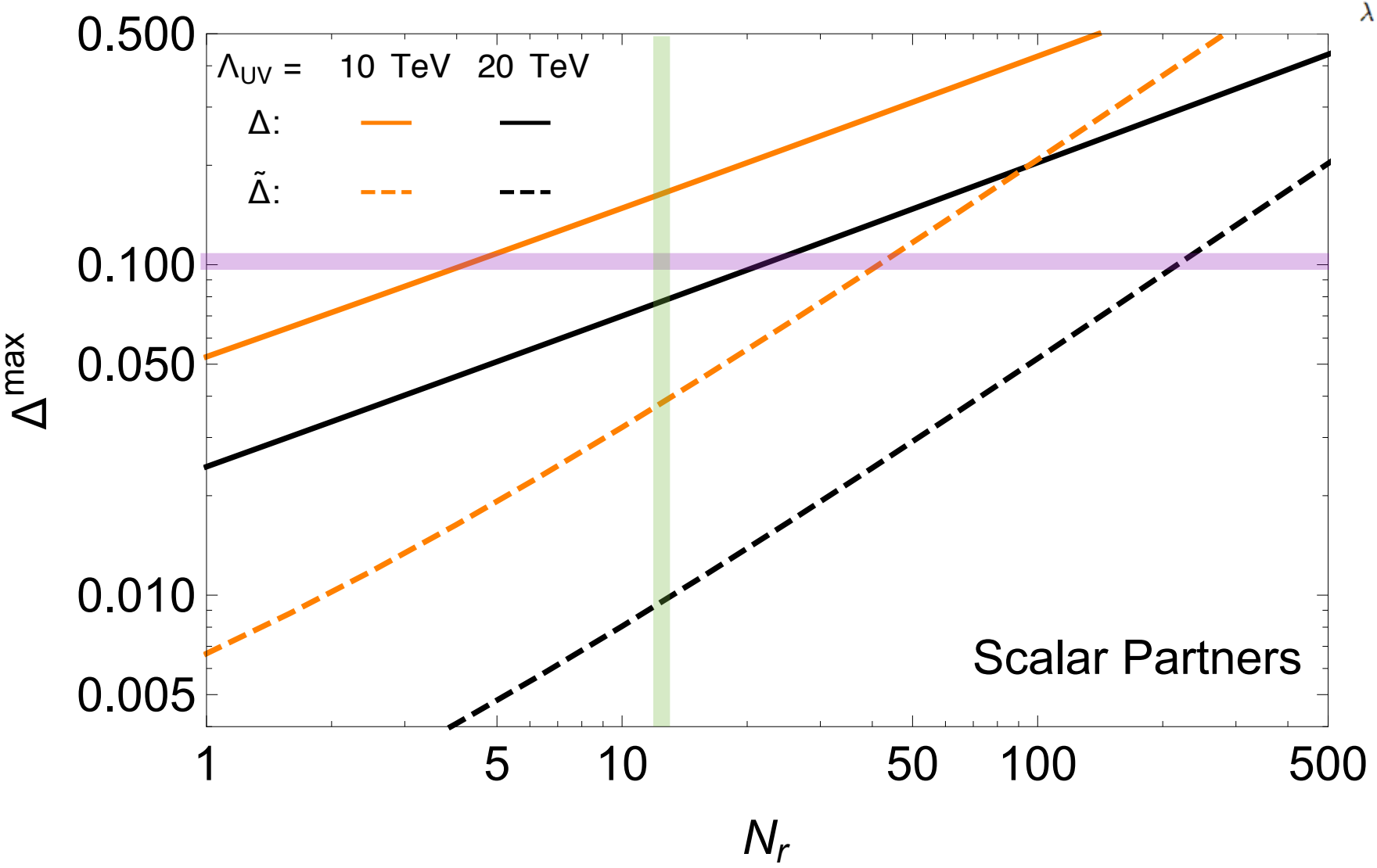
1409.0005: DC, Meade, Yu
1412.0258 Craig, Lou, McCullough, Thalapillil





Scalar Partner

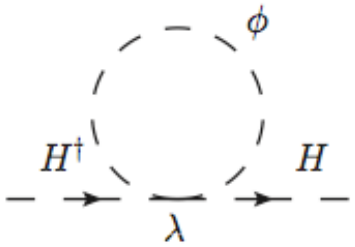




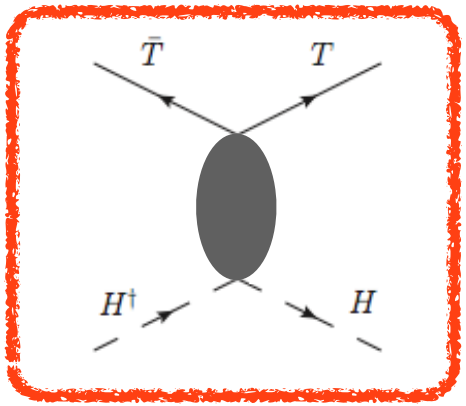
A natural theory needs to have VERY MANY scalar partners to possibly escape detection.

Neutral Naturalness Scenarios

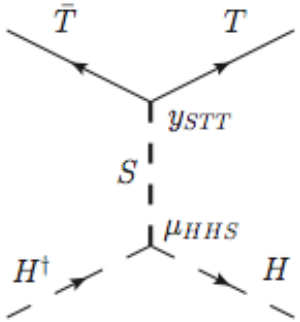
Scalar Partners



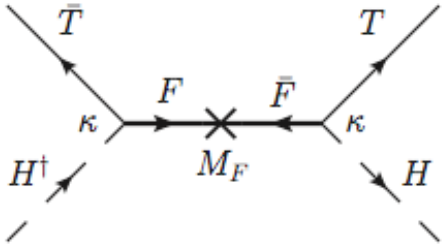
Fermion Partners
(strong coupling)



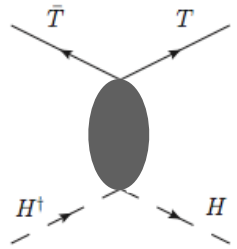
Fermion Partners
(scalar mediator)

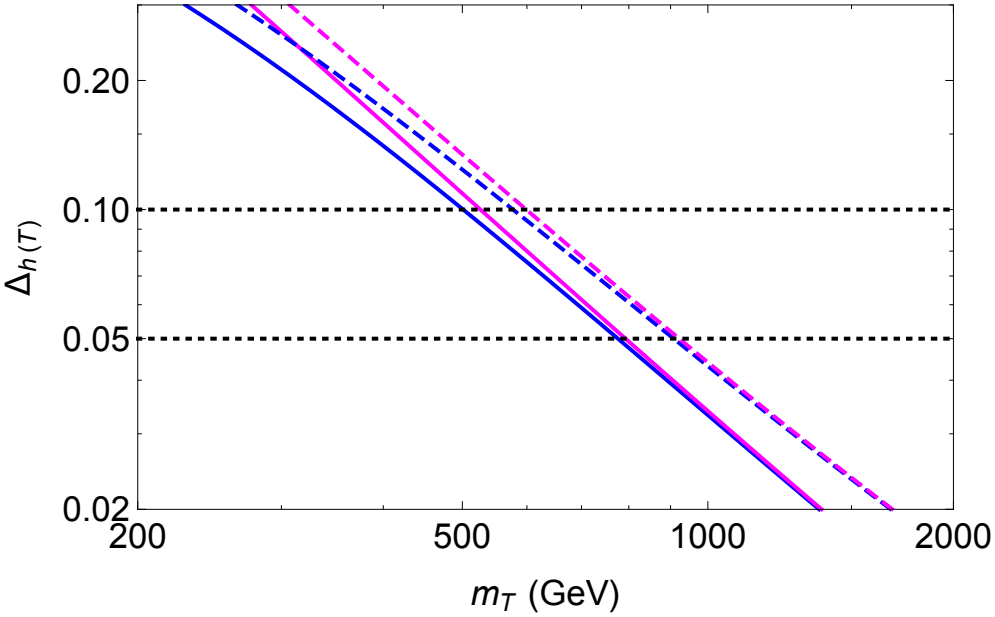


Fermion Partners
(fermion mediator)

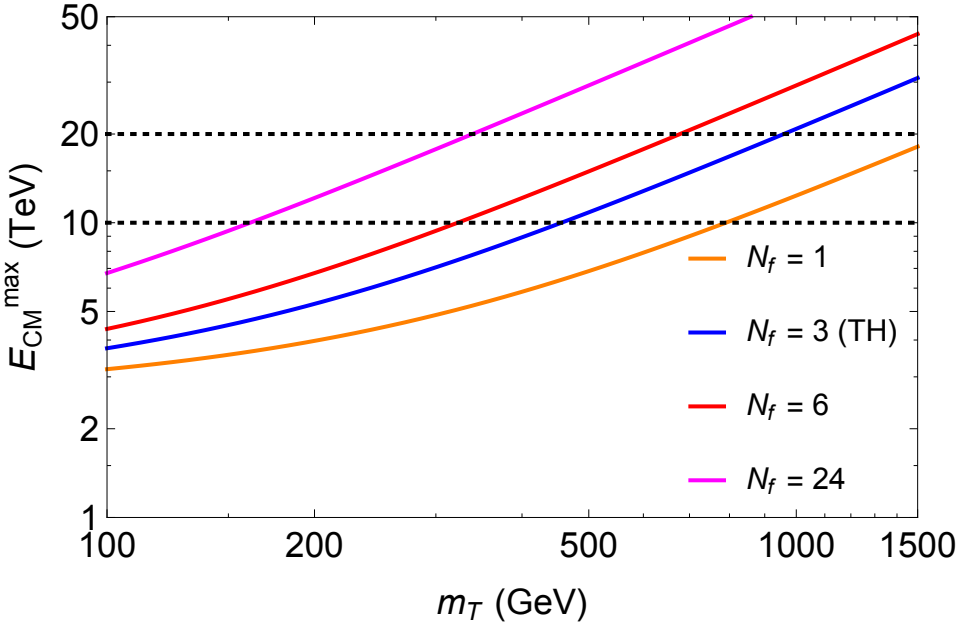


Fermion Partner - Strong Coupling



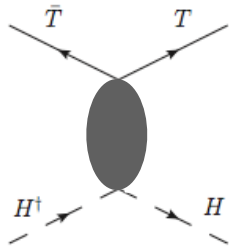


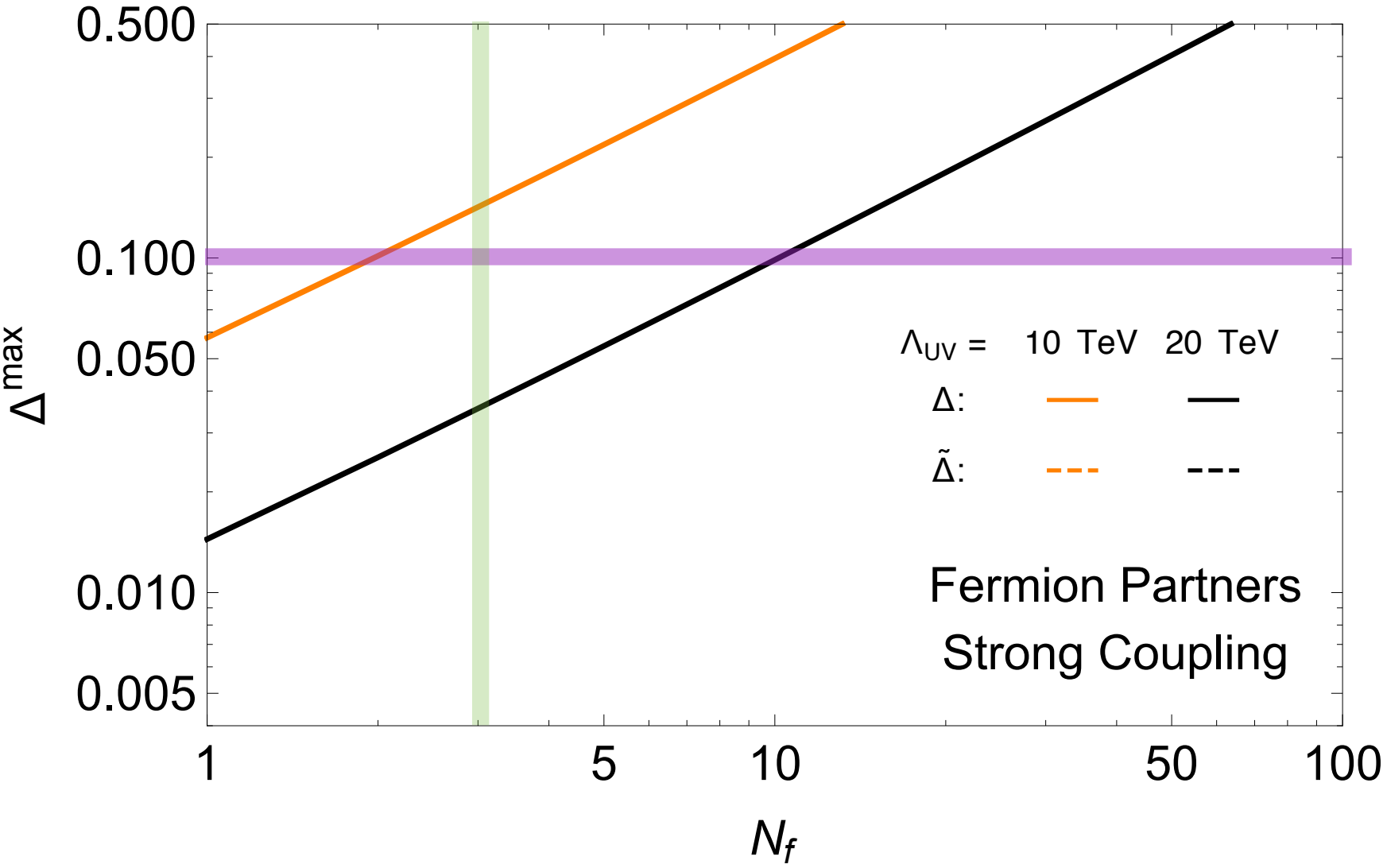
Log tuning of higgs mass:
for Λ_{UV} < 10 - 20 TeV,
$m_T \lesssim$ 500 GeV
OR
tuning worse than 10%.



Unitarity constraints place *strict* upper bound on Λ_{UV} where new physics must get resolved.

Fermion Partner - Strong Coupling





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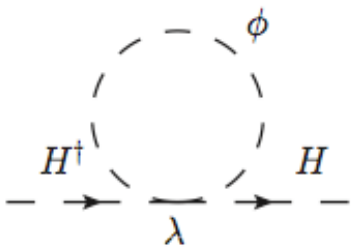
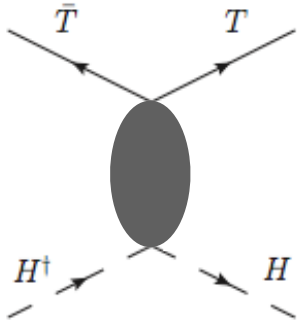
Neutral Naturalness Scenarios

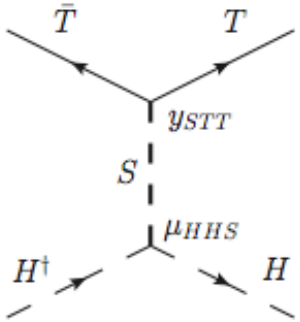
Scalar Partners



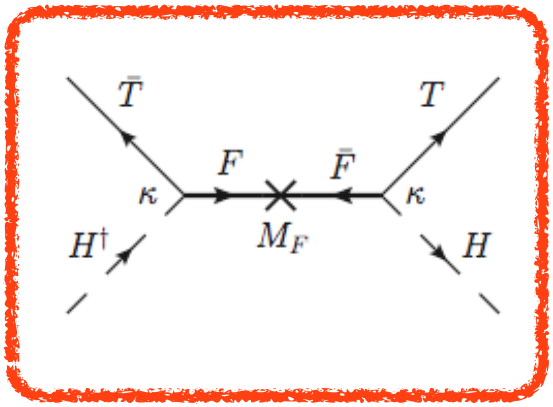
Fermion Partners
(strong coupling)



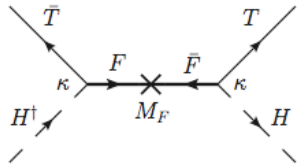
Fermion Partners
(scalar mediator)



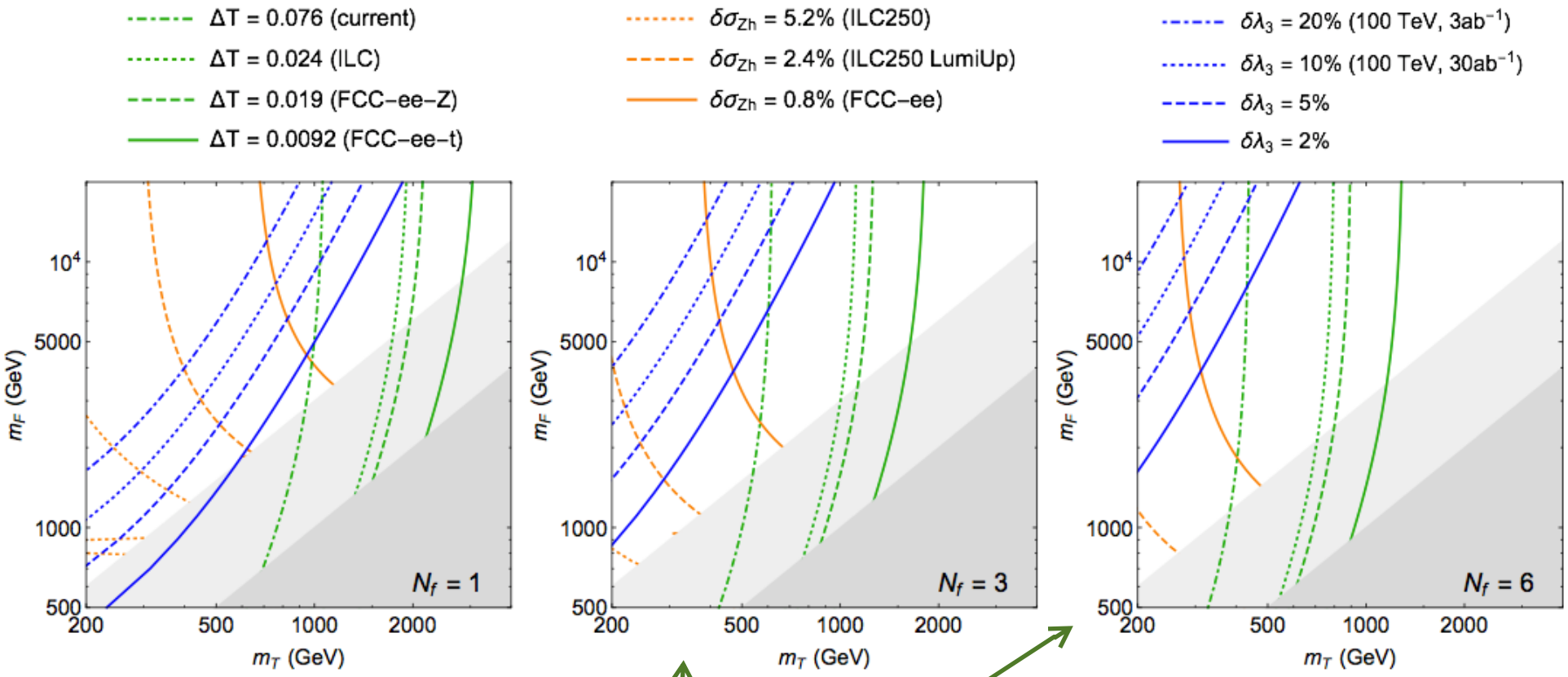
Fermion Partners
(fermion mediator)



Fermion Partner - Fermion Mediator

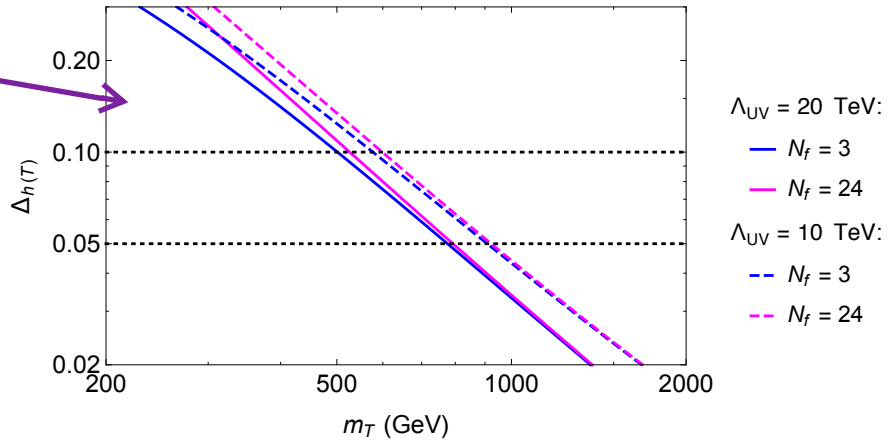


using results from 1506.0546 Fedderke, Lin, Wang

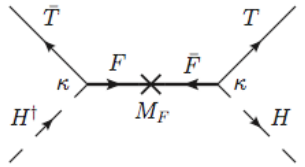


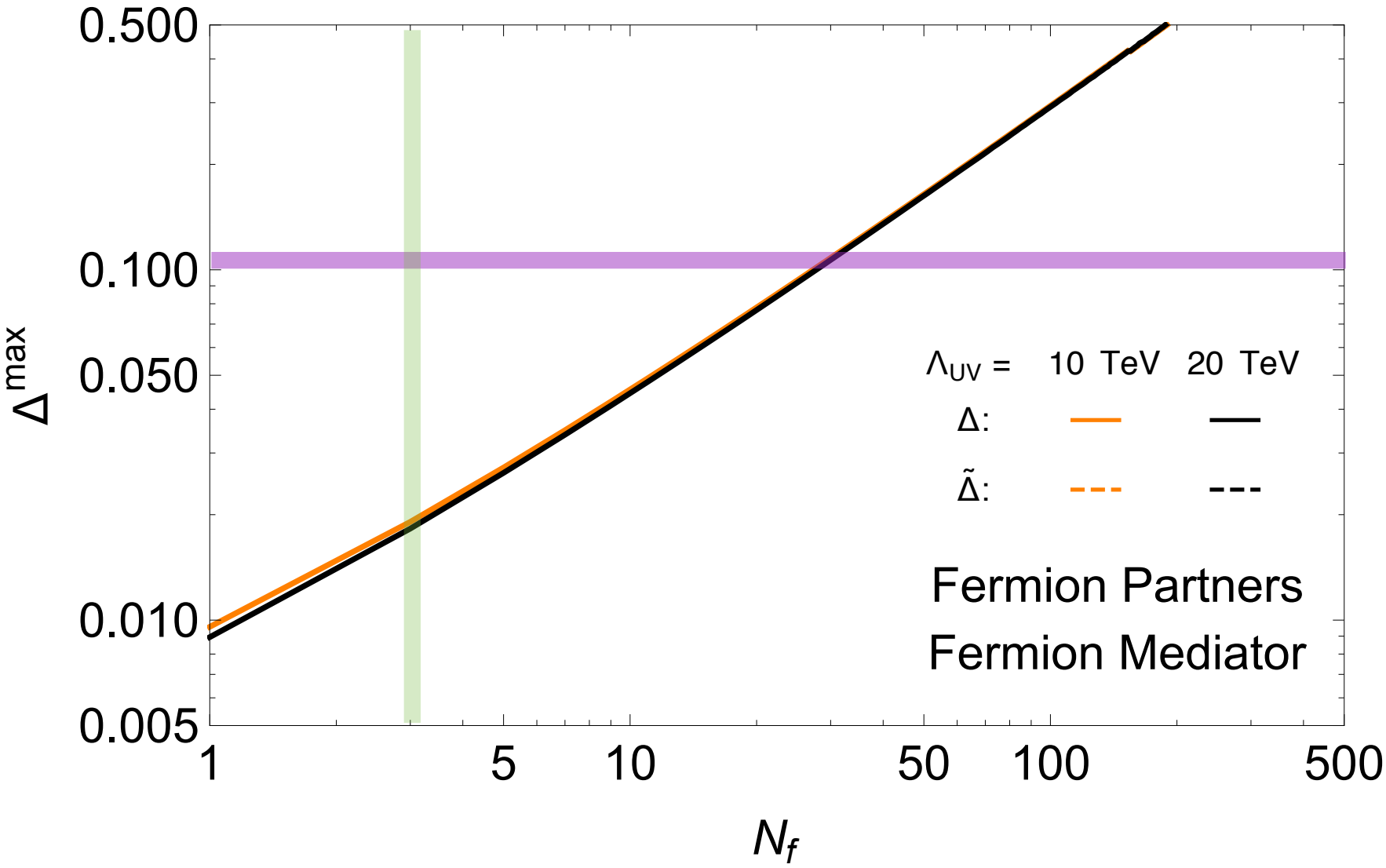
Violation of custodial symmetry → large T parameter deviations!

Again, Higgs log tuning prefers top partners < 500 GeV



Fermion Partner - Fermion Mediator





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